Ministry of Defence

Design of Ships' Structures

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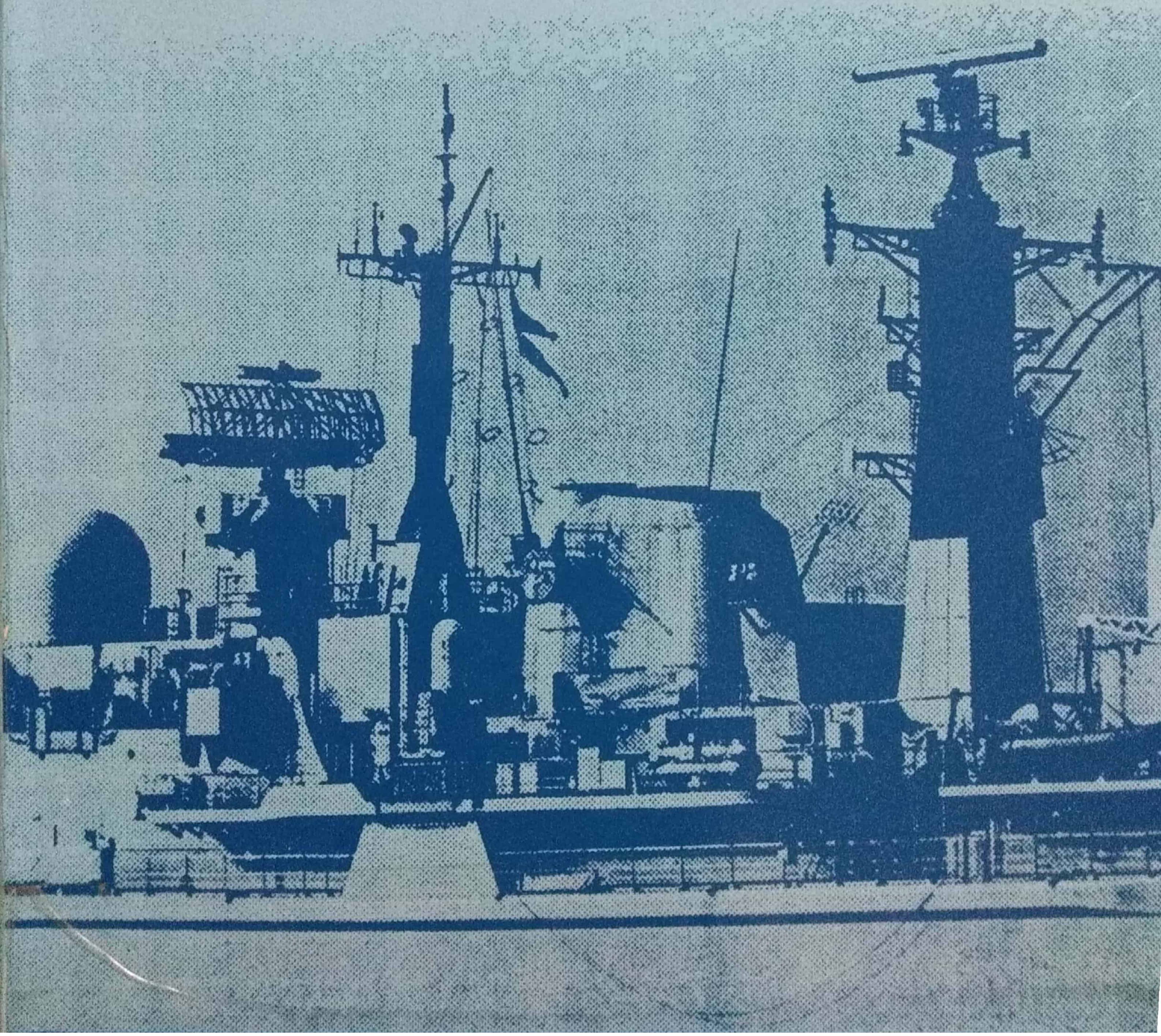

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NOTATION

The following are the principal symbols used in the text of this publication. Because of the complexity of the presentation it is not possible for all the symbols to have unique meanings, and where appropriate a particular meaning in the list below is related to a chapter. If no chapter is referenced then the meaning is generally applicable. Neither is it possible for the list to be exclusive as there are many local variations of the symbols which are defined in the text. Additionally, many of the symbols have suffixes and superfixes; only the most important of these are listed here, the majority being defined in context.

Symbol	*Definition*	*Chapter*
A	Area (defined in text);	
	Length of grillage.	10
A_s	Cross section area of stiffener;	
	Cross section area of superstructure.	8
a	Long or longitudinal dimension of plate panel between stiffeners;	
	Wave amplitude;	3
	Crack half length.	13
$a_{1/10}$	Mean of 1/10th highest accelerations.	
a_t	Length of tyre footprint.	12
B	Beam at waterline amidships;	
	Bending moment in a single wave encounter;	3
	Breadth of grillage.	10
B_s	Breadth of superstructure.	
$\mathbf{B}$	Maximum bending moment on hull.	3
β	Propeller out-of-balance moment.	12
b	Short or transverse dimension of plate panel between stiffeners;	
	Buoyancy/unit length;	3
	Bore of gun.	4

Symbol	Definition	Chapter
b_e	Effective breadth or width of plate.	
b_t	Width of tyre footprint.	12
C	Damping coefficient.	14
C_a	Area coefficient = immersed area/BT.	8
C_b	Hull block coefficient.	
C_D	Drag coefficient.	
C_E	Effective structural weight coefficient.	6
C_p	Hull prismatic coefficient.	
c	Chord length of shaft bracket arm.	12
D	Depth of hull structure.	
D_{na}	Distance between upper deck and neutral axis of hull.	
D_x, D_y	Bending stiffness parameters.	
d	Distance (defined in text); Height of flat bar stiffener.	 18
d_1, d_2	Outer and inner diameter of shaft.	12
d_{na}	Distance between upper deck and neutral axis of superstructure alone.	
d_s	Height of superstructure.	
E	Young's modulus.	
E_s	Secant modulus.	
E_{ss}	Young's modulus of superstructure material.	
F	Force (defined in text).	
$\mathbf{F}$	Total fluid loading on hull.	
f	Natural frequency (Hz).	14
G	Shear modulus.	
g	Acceleration due to gravity.	
$H_{1/3}$	Significant wave height.	
h	Distance (defined in text).	
I	Second moment of area.	
I_{100}	Second moment of area of hull section with superstructure 100% efficient.	
I_L	Pitch inertia.	
$\mathfrak{I}$	Blast wave impulse.	15

Symbol	*Definition*	*Chapter*
J	Torsion constant.	
K	Elastic stress intensity factor.	13
K_m	dynamic magnification factor.	14
k	Radius of gyration of plate and stiffener combination.	
L	Length of hull, usually waterline length;	
	Span of stiffener.	8
L_s	Length of superstructure;	
	in direction of shock front propagation.	4
M	Bending moment.	
M	Concentrated mass	14
m	Mass/unit length.	
m_o	Mean square value of distribution curve.	
m_2, m_4, etc	Second, fourth moment of distribution curve.	
N	Line load/unit length;	
	Number of cycles of encounter;	3
	Maximum propeller rpm;	12
	Hull natural frequency.	14
N,**N**	Fatigue endurance limit in cycles.	13
N_f	Number of cycles to failure in one stress range.	13
N_s	Number of slams in unit time.	
n_L	Number of wave encounters in ship's life.	13
P	Pressure;	
	Applied load due to aircraft landing.	12
P_d	Probability of exceedance of design bending moment in n_L cycles.	13
p	Pressure.	9
Q	Shear force;	10, 18
	Force/unit length.	
q	Shear flow (not Chapter 9);	18
	Lateral pressure.	10, 18
r	Number of stiffeners on grillage.	
S	Plastic section modulus.	

Symbol	*Definition*	*Chapter*
S,S	Fatigue stress range.	13
S_c	Half height or half breadth of deckhouse.	4
s	Distance (defined in text);	
	Number of stiffeners on grillage;	10, 18
	Permanent set in plate.	12
$\dot{s}_*$	Threshold relative velocity for slamming.	
T	Draught;	
	Wave period (or period of motion);	3, 4
	Material shear strength.	5
T_f	Draught at forefoot.	
T_m	Missile thrust.	4
t	Time or plating thickness (see context).	
t_p	Thickness of plate.	18
t_s	Duration of reflection and refraction phase of shock wave;	8
	Thickness of superstructure side plating;	8
	Thickness of flat bar stiffener.	18
U	Velocity of shock wave front.	
U_o	Ambient speed of sound.	
u	Distance (defined in text).	
V	Ship or wind speed (see context);	
	Compartment volume.	15
W	Weight (defined in text);	
	Weight/unit area.	8
w	Weight/unit length;	
	Spacing between twin wheel centres on aircraft;	12
X	Material strength in x direction.	
x	Coordinate, +ve forward from amidships.	
x_e	Maximum elastic deformation under air blast load.	8
x_{max}	Maximum deformation under air blast load.	8
Y	Material strength in y direction.	
y	Coordinate, +ve to port from centreline.	
Z	Hull section modulus.	

Symbol	*Definition*	*Chapter*
z	Coordinate, +ve upwards from base line.	
z	Vertical displacement of hull.	
α	Aspect ratio of plate panel between stiffeners ($\leqslant 1.0$);	
	Missile thrust angle;	4
	Angle of action of rotating force on shaft bracket.	12
ß	Plate slenderness ratio $= (b/t)\sqrt{(\sigma_y E)}$;	
	Semi-angle of missile efflux cone;	4
	Safety index;	11
	Semi-angle between shaft bracket arms.	12
Γ	Warping constant *(also gamma function)*.	
Δ	Displacement, usually deep.	
Δ_1	Displacement including added mass.	14
δ	Logarithmic decrement;	14
	Deflection of plate.	18
E	Energy/unit area in wave.	
ε	Strain.	
ζ	Wave elevation.	
η	Efficiency.	
η_{ss}	Superstructure efficiency.	
θ	Amplitude of angular motion.	3
	Rate of hull twist $= \partial\vartheta/\partial x$.	7
ϑ	Angle measure;	
	Twist of hull;	7
	Pitch angle, +ve bow down.	3
λ	Column slenderness ratio $= (a/\pi k)\sqrt{(\sigma_y/E)}$;	
	Wave length.	3
μ	Mean value.	11
ν	Poisson's ratio;	
	Damping ratio.	14
Ξ	Wave spreading function.	
χ	Wave direction.	
ρ	Density of water.	

σ	Direct or bending stress;	
	Standard deviation.	11
σ_y	Yield stress of material (except Chapter 5).	
T	Torque on hull;	
	Period of oscillation.	14
τ	Shear stress.	
Φ	Energy distribution spectrum.	
φ	Phase difference;	
	Hull curvature.	7
ψ	Angle of flare;	
	Deck flexibility factor.	8
ω	Wave frequency.	3
ω_o	Natural frequency (rad/s).	14
ω_e	Encounter frequency.	

CHAPTER 1

Introduction

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CHAPTER 1

Introduction

The Aim of this Publication

1 Structural design of ships' hulls is, in general, an iterative process in which there are the following main steps:

a. To decide which are the most important loads on the structure for its expected operational life, and the equivalent critical modes of failure;

b. To propose and develop a structural configuration and to make a preliminary estimate of weight and centre of gravity;

c. To create a model (or mathematical idealisation) of the proposed structure which is sufficiently representative of the real structure in all important aspects;

d. To analyse the model and compare its performance against specified design criteria for the agreed failure modes;

e. To modify the structural configuration to achieve adequate performance while at the same time avoiding the use of superfluous material and unnecessary cost.

2 The aim of this book is to provide guidance on each of these steps but not to specify particular acceptance criteria. These will vary with the rôle and requirement of the vessel being designed and, while advice will be offered, it must be for the designer to make a final choice of margins for the appropriate level of safety and reliability. However, standards and acceptance criteria will usually be laid down or otherwise specified in the design contract. The following chapters will take the designer through the iterative structural design process starting at Chapter 3 with **Loading** and ending at Chapter 11 with **Optimisation**. The remaining chapters cover aspects of structural design which are relevant at all stages.

The Aim of Structural Design

3 The purpose of structural design of ships is to design the most efficient structure for the requirement, where 'efficient' is defined in the widest sense taking account of first cost and through life cost. For a commercial vessel an efficient structure is that which yields the greatest ratio of total earnings to expenditure over a defined life. For a military vessel it is not usually

possible to define the benefits in monetary terms, but an efficient structure is one which, taken together with all the other parts of the ship, requires the minimum expenditure through life. However, a true estimate of these costs is never available and indeed if the cost of loss of operational availability is taken into account while the ship is under repair, it is probably impossible to estimate. Consequently the structural designer has to be fully aware of the effects of his design decisions on the cost of construction and maintenance. It will usually be the case that the simpler structures will be the cheapest in the long term even if they are not the lightest in weight.

The Rôle of the Designer

4 The rôle of the structural designer changes as the design develops and his function is different at each phase of the design. In particular, he must not go into more detail than is necessary for the immediate requirement; for example, in the early stages when a number of different designs are being considered, he need go no further than estimate mass, centre of gravity, cost and possibly reliability, while at the same time ensuring satisfactory structural continuity. At each further stage these estimates will be refined and more detail added. However, at all times he must be sure than the structural concept is designable and that all the estimates, including those for other parts of the ship where they interact with the structure, are consistent. That is, he must be satisfied that the overall architecture of the design is such that a structural solution can be achieved within the estimates of weight, space and cost, at the same time as ensuring that requisite levels of reliability and maintainability are achieved (see Chapter 16). Where necessary he must also specify margins to take account of the degree of uncertainty implicit at the particular stage of design, leading finally to margins sufficient to allow for operational usage and growth during life.

The Evolution of the Design

5 The design of any complex structure passes through a series of evolutionary phases. In the first phase, when the concept and rôle are being developed, several radically different alternatives will be considered in sufficient depth to identify a small number of promising design options. Amongst many factors considered in this phase will be alternative structural configurations and materials, comparing possible solutions with requirements such as vulnerability and structural survivability while satisfying design constraints such as the need to avoid stress concentrations and to provide adequate load paths. In succeeding phases the refined options are considered in greater depth until the most efficient arrangement can be identified for full development. The final phase then involves complete analysis of the design to prove it against its intended rôle.

6 The titles given to the design phases have differed widely with time and between different organisations. For example, the terms 'concept' and 'feasibility' for warship design have opposite meanings on either side of the Atlantic. In this book no particular stance is taken, and to preserve generality the first attempt will be called 'initial design' and each subsequent change will be called an 'iteration', numbered appropriately.

7 The structural designers' greatest impact on the overall ship design can be made only in the earliest stages and, in particular, the initial one when different configurations are being studied and are being considered on their merits in relation to other design aspects and to the vessel's rôle. In later stages the main configuration is fixed and places a major constraint on the design, and so any innovations must be introduced early. However, because early constraints on the design are inevitable, it follows that many of the principal structural characteristics are predictable at these early stages, and this aspect will be explored further under the heading of **Structural Synthesis** in Chapter 6. It should not be taken from this, however, that the structural designer has little to offer at the later stages of design. The cost of maintaining a structure is critically dependent on design and construction of details and these must be controlled with great care, especially as that part of the design is usually carried out at technician level.

Synthesis, Analysis and Optimisation

8 Another way of looking at the design process is through the concept of synthesis, analysis and optimisation:

a. *Synthesis* - is the development of a system from its components while ensuring compatibility between components, loads and in-service functions;

b. *Analysis* - is the proof that the synthesised system will provide the required functions with acceptable reliability when subjected to service loads;

c. *Optimisation* - is the process of ensuring that the system as analysed is the most efficient and economic means of providing the required function.

Clearly the design must proceed initially in the order synthesis, analysis, optimisation, but the effort put into each and the methods used will differ widely in different contexts, and as the design iterations progress the three processes will overlap and become mixed. This book will give guidance on all three but with emphasis on synthesis, and with comprehensive references to analysis and optimisation. However, where techniques are not readily available they will be covered in some detail herein.

9 Techniques of optimisation will be considered in Chapter 11, but minimisation of through life costs depends on the ruggedness of the structure and its ability to accept use and misuse without unacceptable deterioration in reliability. Thus a slightly heavier structure which is a little more costly in material may be cheaper in the long term as it is less sensitive to corrosion and local deformation and therefore needs repair less often. At the same time the heavier structure may be easier to assemble and require less rework (straightening out structure deformed in the process of assembly, mainly due to welding effects) and so may actually be cheaper to build as labour costs are less. Overall optimisation will lead to a compromise between size, complexity, initial costs and maintenance costs. Conventional ships are not especially weight critical compared, for example, with aircraft, and in general it will not be possible to estimate overall costs with sufficient accuracy to provide a logical argument for restricting structural weight, particularly when it is considered that the cost of materials for primary structure for conventional hulls is a very small proportion of total ship cost (1-2% for a frigate). The argument will be somewhat different for weight sensitive vessels such as Small Waterplane Area Twin Hull (SWATH) ships or Surface Effect Ships (SES).

Historical Perspective

10 To assist in understanding the design process, a study of the history of ship design is invaluable, not the least to ensure that past mistakes are not repeated. In the current context a brief summary of recent experience is presented, and a more detailed discussion of the history of the estimation of hull loading is given in Chapter 3, as the present position on loading is particularly dependent on past practice and historical data.

11 For the whole of this century up to the mid 1970s the method of assessing wave loading on a ship was to carry out a static balance on a wave. The wave height taken for RN ships was L/20 (L is the ship length of the waterline) but elsewhere in the world, and for merchant ships, a height of $0.6\sqrt{L}$(metres) ($1.1\sqrt{L}$ for L in feet) was more common. The use of L/20 might have led to some conservatism in larger ships (of length more than about 150 m) as the likelihood of meeting the larger wave reduces progressively with size. However, this was commonly compensated for by allowing higher stresses in longer ships. Because the L/20 wave was a severe but not extreme one, and could be met fairly frequently, the bending moment so derived was used in association with a stress factor generally not less than 2.5 between yield stress and average distributed stress in the structure furthest from the neutral axis. Some buckling checks using classical methods (generally elastic Euler buckling) on single stiffeners and associated plating were also undertaken.

12 In the 1950s and 1960s methods were formalised for checking the buckling strength of components in ship structures, in particular the use of iterative elasto-plastic techniques for assessing the critical stresses for column buckling of longitudinal stiffeners with initial imperfections. Due to welding distortions it was assumed that plating between stiffeners was effectively buckled in the unloaded condition. However, overall buckling of an orthogonal grillage could only be assessed in an ideal undeformed state. A large margin (around 5.0) was therefore applied to this latter condition, while a margin of at least 2.0 was required for the column buckling case against the L/20 wave bending stress.

13 There was no explicit means of allowing for fatigue in design in that period. Historically, for rivetted ships, cracking was likely to occur in a single plate only and cracks were expected to be arrested at rivetted joints. For the first all welded ships designed in the 1940s and 1950s, good attention to detail was deemed adequate, associated with the relatively low field stresses which were necessary for acceptable resistance to buckling. It is notable that, except for areas of poor local detail which were attended to early in life, all ships designed at that time have achieved over 20 years of life and have only been operationally restricted by fatigue failure at around 23 to 25 years. Nevertheless, they have required some repair at every refit.

14 In the 1950s and 1960s brittle failure was seen as a problem due to the relatively poor steel quality available and the transition to all welded structure. This was solved by the introduction of notch tough steels into naval service, but the early all welded vessels always had rivetted crack arresting strakes in the hull.

15 In the mid 1970s two significant developments took place. The first was intended as a more objective means for calculating wave bending moments using rigid body dynamics associated with the statistics of seas in which the ship was expected to operate. The second was a method of calculating the ultimate collapse strength of a hull as a complete entity rather than in a piecemeal manner, and allowing much more accurately for the effects of hull shape and for initial imperfections. Additionally, methods of Finite Element Analysis (FEA) became more readily available for detailed elastic analysis of structures. All these techniques took account of the increased electronic computing power that was becoming available to the designer.

16 The new method of estimating design bending moments known as 'strip theory' involved assuming the ship to be a wall-sided non-uniform beam, and for a particular set of sinusoidal wave excitations, solving the equations of motion to find the shear forces and bending moments. Then, for an appropriate set of wave frequency spectra, linear superposition is used to estimate the mean square bending moments for each spectrum. Finally, from an assumed operational scenario in terms of probabilities of meeting particular wave heights at particular speeds and headings, a plot of bending moment against probability of exceedance in a specified time period is deduced. However, because the method takes no account of the effects of non-linear ship shape or of non-linear wave effects under the extreme conditions appropriate to the design point, it overestimates the bending moment compared with measurements from ships in service as discussed by Clarke (1986). It was therefore necessary to collect measured data and to extrapolate this to the same design point as the theory so as to yield a factor by which to modify the theoretical solution. The scatter between ship classes which is apparent in obtaining the factor has since shown the method to be somewhat unreliable, and in need of confirmation by deterministic methods.

17 Because the method was intended to be used as part of an *Ultimate Limit State* analysis of the hull, the design point, that is the bending moment and shear force to which the structure was designed, was set at an extreme value with a low probability of exceedance in a ship's life. During the scaling of the theoretical results to match the measurements from sea a probability level was set at about 1.5% in 3×10^7 wave encounters. For an average wave period this number of wave encounters was equivalent to about 22 years of life with 30% spent at sea in average North Atlantic conditions. The previously used design point derived from static balance on an L/20 wave was a severe condition but likely to be met with much greater frequency than the 1.5% probability condition and consequently the results from the two methods could not be directly compared. New safety margins had to be laid down on the basis of engineering judgement with little practical data on which to base them and, as stated above, there was considerable scatter in the results when attempts were made to reanalyse earlier designs to provide better substantiated values.

Current Designs

18 Following the changes that took place in the design process in the 1970s, it is worthwhile studying briefly the resulting hull designs and drawing some conclusions. Perhaps the most important point to note is the advantage of following an evolutionary line. The more successful British designs since World War II, for example the LEANDER, TRIBAL and Type 22 Classes, all follow logically from previous successful designs with due allowance being made for known deficiencies in the earlier ships. In the case of the TRIBAL Class, where a large evolutionary step was taken involving heavier structure transversely framed at the forward end, intended to reduce maintenance, more detailed analysis was undertaken and larger margins used in areas of uncertainty. The less successful designs are those in which inconsistent sets of design data have been taken from different type ships resulting in a 'lowest common denominator' solution, or where something quite different has been attempted without a clear understanding of the implications or at least a large margin for error. It is always a false economy to try to save cost by reducing margins and so increasing design risk.

19 Another important point to be noted is the need to design the ship for a realistic life. Whatever is hoped for in the original requirements, much is likely to change during the ship's life and, for warships at least, the RN is always short of hulls. Experience shows that 25 years is a practical life span for some, if not all, of a class of ships and the hull should be expected to last for that time without too severe a burden on the maintainers. In any case, there is very little to be saved in attempting to design a short life hull while there is much to be lost in sacrificing robustness and resistance to wear and tear.

Commercial Standards

20 There has, on occasions, been pressure to use so-called commercial standards for warship hull structure. The first thing to note is that 'commercial standards' is a very vague term and is certainly not something that can be quoted contractually. In practice, what is probably intended is a hull to Classification Society Rules using materials and standards similar to those used in merchant vessels. Such a hull is not possible as there are no Classification Society Rules for warships but only for ship types, such as trawlers or RO-RO ferries which might be construed as being similar to a warship style. The important point to remember is that all these ships are designed for a particular and definitely non-warlike rôle, and that the implicit requirement of a warship to withstand hard usage is severe weather conditions, including impact and explosive loading, are rarely part of a commercial specification. In particular, a warship will need to be built of notch tough steel to avoid brittle fracture if it is to operate in sub-arctic conditions, and the details of the structural connections will need to be carefully thought out to limit fatigue damage in normal use and rupture following underwater explosion loading. Consequently, in a well designed warship, 'commercial standards' are unlikely themselves to save much if any money, while pursuing the idea of a commercial hull in preference to warlike standards will considerably increase the risk both of the loss of the ship in war and loss of operational availability in peacetime. A more logical way of saving money without greater risk would be to accept larger, more robust and less congested hulls using well proven warship technology.

Practical Designs

21 All aspects of the design process, the environment, the loading and the response of the ship, are recognised to be essentially non-linear and so very difficult to model mathematically. In practical terms the linear limitations of most methods of synthesis and analysis must be recognised. The skill of the designer lies in his ability to adopt highly simplified models of what he believes from his experience to be the most important parts of the design, and his ability to use the results of past practice to validate the approximate models.

22 An extreme form of such a simplified approach is that traditionally used by the Classification Societies, where an extensive knowledge of past practice has been used to provide designers with simple tables and formulae with which to create and analyse their designs. Over the past 20 years, however, there has been a change towards a so-called rational or fundamental approach based on improvements in the statistical description of the sea surface and the calculation of rigid and flexible body response to changes in the shape of the sea surface. These improvements in techniques have been paralleled by advances in structural analysis using computers to solve the resulting vast numerical problems, the two together enabling the designer to pursue his objective in a far more sophisticated manner. This leads him to a problem at another level, that of how sophisticated he should be. In the field of design, as well as construction, greater complexity costs money and the designer is confronted with another stage of decision making in which he has to conclude whether the extra effort put into a higher degree of analysis when design resources are scarce is balanced by a saving in cost or reliability in the resulting structure. In any case it is vital that a consistent philosophy is followed and results are validated against conventional designs. These points are discussed in more detail in the chapters on loading and strength.

23 When embracing new technology it is particularly important that all the potential pitfalls are understood and that new design methods and new materials are used within their limitations. Provided the evolutionary approach is followed, and the designer starts with a consistent set of design assumptions, a valid concept and adequate margins, there is every reason for suppose that a reliable and cost effective solution will result. Whenever significant departures from established and proven structural styles are made, risk increases significantly, as the designer will have difficulty in comprehending many of the implications. Even when the level of risk is realised, it may be difficult to sustain the necessary margins against pressure to reduce cost or weight. The desirable low cost, low risk design can only be achieved if departures from established practice are concentrated on reduction of construction labour man-hours by producing a simple structure which will still have well known characteristics and failure mechanisms under the conditions in which warships must operate. That is not to say that modern analytical techniques should not be used, but that the results should be compared with past successful practice and any unexpected deviations properly explained.